WHITE PAPER

SUMMARY OF RESEARCH RELATED TO TRANSPORTATION OF JUVENILE ANADROMOUS SALMONIDS AROUND SNAKE AND COLUMBIA RIVER DAMS

Northwest Fisheries Science Center
National Marine Fisheries Service
2725 Montlake Blvd. E.
Seattle, Washington 98112

September 1999

CONTENTS

BACKGROUND

Since the late 1960s, transportation of juvenile salmonids by truck or barge has been studied extensively by the National Marine Fisheries Service (NMFS) in the Federal Columbia River Power System (FCRPS). On the Snake River, transportation of steelhead (*Oncorhynchus mykiss*) and yearling chinook salmon (*O. tshawytscha*) was evaluated at Ice Harbor, Little Goose, and Lower Granite Dams from 1968 through 1980, and again at Lower Granite Dam in 1986 and 1989. More recently, transportation of yearling chinook salmon was evaluated using PIT-tag technology in 1995, 1996, 1998, and 1999 at Lower Granite Dam; steelhead were also PIT tagged for evaluation in 1999. On the Columbia River, transportation of steelhead and subyearling chinook salmon was evaluated at McNary Dam from 1978 through 1983, and yearling and subyearling chinook salmon were evaluated from 1986 through 1988. In addition, transportation of sockeye salmon (*O. nerka*) was studied at Priest Rapids Dam during 1984-88.

The NMFS has conducted research for more than 25 years to evaluate whether transportation of juvenile fish from upper Snake River dams increased adult returns compared to returns from juvenile fish that migrated through the hydropower system. The general methodology for all of the studies was to collect fish at a dam and mark two groups--one for transportation and one for migration through the hydropower system. Fish for transportation were placed into either trucks or barges, transported below Bonneville Dam, and released. Fish marked to evaluate migration through the hydropower system were generally trucked and released a few kilometers upstream of the dam where they were marked, or trucked downstream below Little Goose Dam and released. In the late 1970s, some control fish were released directly into the tailrace of Lower Granite Dam, but an unknown number were likely subsequently collected and transported from Little Goose Dam.

In the various studies, the smolt-to-adult return (SAR) of transported fish was compared to the SAR of control fish (intended to represent inriver migrants) and expressed as a transport-to-inriver adult return ratio (T/I). The T/I was based on results pooled from individual mark groups. For most evaluations, smolts were marked and transported from one site. Smolts that migrated inriver were released at the marking site or were transported a short distance above or below the marking site and then migrated inriver.

Adult returns from nearly all studies conducted between 1968 and 1989 indicated higher SARs for transported than for inriver migrant study fish. Nonetheless, overall SARs were, in nearly all cases, much lower than SARS estimated prior to completion of the lower Snake River dams and John Day Dam on the lower Columbia River. In spite of the higher SARs of transported fish, many in the fisheries community suggested that transportation was ineffective because absolute SARs were below historic levels.

Additionally, over roughly the last 18 years, various researchers have also evaluated and measured smolt performance, stress, mortality, disease transmission, and behavior relative to transportation. Results of all these studies have been used to manage the juvenile fish transportation program over the years.

Few, if any, anadromous salmonid mitigation techniques have received such intense scientific scrutiny over such a protracted period. Results of this scientific endeavor are summarized here.

TRUCK TRANSPORTATION

Truck-transportation evaluations began at Ice Harbor Dam in 1968 and continued at various dams until the mid-1980s; however, the majority of studies were conducted during the 1970s. Studies were conducted on yearling and subyearling chinook salmon, steelhead, and sockeye salmon. No contemporary information is available on truck transportation.

Yearling Chinook Salmon

Snake River Studies

Over the course of 16 truck-transportation studies conducted at Snake River dams from 1968 through 1980, T/Is ranged between 0.7 and 18.1, with 2 of the studies reporting T/Is below parity and 2 studies reporting no adult returns of either study group (Ebel et al. 1973, Slatick et al. 1975, Ebel 1980, Park 1985). In six of the studies, significantly more transported fish than control fish were recovered as adults, indicating higher survival for the transported groups. In only one study were significantly more control fish recovered than transported fish. In 10 tests, adult recoveries of both test groups were too few to identify statistically significant differences between returns of transported and control fish; however, more transported than inriver-migrant study fish returned in most of these tests (Park 1985).

Subyearling Chinook Salmon

McNary Dam Studies

Six subyearling chinook salmon truck-transport evaluations were conducted at McNary Dam from 1978 through 1983. In all studies, significantly more transported than inriver-migrant study fish were recovered as adults from all recovery areas. For fish recovered at dams, T/Is ranged from 2.3 to 10.1.

Steelhead

Snake River Studies

From 1970 through 1978, 13 separate steelhead truck-transportation studies were conducted at dams on the Snake River. In all 13 studies, steelhead that were transported as juveniles returned as adults at significantly higher rates than did those that migrated inriver, with T/Is that ranged from 1.5 to 13.5 (Ebel et al. 1973, Slatick et al. 1975, Ebel 1980, Park 1985, Matthews 1992).

McNary Dam Studies

Three truck-transportation studies were conducted on steelhead at McNary Dam from 1978 through 1980. Significantly more adults were recovered from groups that were transported than from groups released as inriver control fish in two of the studies. In the other study, the trucked group returned at only a slightly higher rate than the inriver control (the difference was not statistically significant). The T/Is ranged from 1.3 to 3.0 (Park et al. 1984).

Sockeye Salmon

Priest Rapids Dam Studies

The only data available on transportation of sockeye salmon (*O. nerka*) are from studies conducted by truck from Priest Rapids Dam between 1984 and 1988 (Carlson and Matthews 1991, 1992). In 1987 and 1988, fish were trucked to McNary then transferred to a barge for the remainder of the trip to below Bonneville Dam. Final statistical analyses were not reported for these studies. The reported preliminary T/Is varied widely, ranging from 0.55 to 4.23.

BARGE TRANSPORTATION

The initial barge-transportation evaluations were conducted at Lower Granite Dam on the Snake River from 1977 to 1980. A second round of evaluations were conducted in the mid- to late 1980s. Studies were conducted on yearling and subyearling chinook salmon and steelhead. In 1995, a new round of evaluations began using passive integrated transponder (PIT) tags as the marking methodology. Yearling chinook salmon smolts were marked with PIT tags in 1995, 1996, 1998, and 1999 and steelhead smolts were also marked in 1999. Barge studies were also conducted at McNary Dam in the late 1970s and early 1980s.

Yearling Chinook Salmon

Snake River Studies

From 1977 through 1980, four barge-transportation studies were conducted on yearling chinook salmon at Lower Granite Dam. In two of the studies (1977 and 1980), no adults returned from either study group. Significantly more transported than inriver-migrating study fish returned as adults during the other two studies, with T/Is of 8.9 and 3.9 for 1978 and 1979, respectively.

A second 3-year barge-transportation study on Snake River yearling chinook salmon began at Lower Granite Dam in 1986. However, no studies were conducted in the low-flow conditions in 1987 and 1988 because the fishery management agencies were primarily interested in evaluating transport in average to above average flow years as the general consensus was that transportation was superior to inriver migration during low flow years. Subsequently, only two years of the planned study were completed--1986 and 1989. Results of the 1986 research indicated a T/I of 1.6, with a 95% confidence interval (CI) between 1.01 and 2.47 (Matthews et al. 1992). Studies in 1989 indicated a T/I of 2.4, with a 95% CI between 1.4 and 4.3.

The latest barge transportation evaluation began in 1995. In each year (except 1997), yearling chinook salmon smolts were inserted with PIT tags to evaluate transportation vs. inriver migration from Lower Granite Dam. However, unlike most previous studies, the inriver fish were released directly into the tailrace of the dam, after collection and marking. Previously applied fin clips were used to identify hatchery fish from wild fish in both the test and control groups during tagging for the study. The Lower Granite Dam study was expanded in 1999 to include steelhead smolts. From the 1995 marking, 726 hatchery and 140 wild adults were recovered at Lower Granite Dam. For hatchery fish, the overall T/I was 2.0 (95% CI of 1.7-2.1); for wild fish, the overall T/I was 2.1 (95% CI of 1.7-2.6). However, T/Is for both hatchery and wild fish tagged in April were roughly 1.0, but increased to between roughly 2.0 and 5.0 for fish tagged in May. The main reason for this difference was that SARs of transported fish increased sharply and abruptly in early May, while SARs of inriver fish simply trended downward throughout the spring. It is speculated that marine predators impacted the survival of fish transported in April, but did not impact inriver-migrating fish to the same extent since they arrived at the ocean 18-21 days behind transported fish and the majority of them did not arrive at the ocean until after the abrupt increase in SARs had occurred for transported fish in early May. Hence, the 1.0 T/Is for fish tagged in April. Adjusting for time of ocean entry resulted in T/Is between 1.7 and 2.0 for hatchery and wild fish, respectively. For the 1996 study year, analyses on adult returns are incomplete; however, adult return numbers and SARs are much less than for the 1995 outmigration (98 hatchery and 13 wild fish). Preliminary T/Is are 1.4 and 2.7 for hatchery and wild fish, respectively. For the 1998 study year, only jack returns are available and 61 hatchery and 6 wild jacks have been recovered at Lower Granite Dam. Initial T/Is are 1.4 for hatchery fish and 7.1 for wild fish.

McNary Dam Studies

In the late 1980s, a 3-year barge transportation study was conducted on yearling chinook salmon at McNary Dam on the lower Columbia River. Insufficient numbers of adults returned for analysis for the 1986 study year. The 1987 study showed a positive association between transportation and survival of yearling chinook salmon, based on a pooled T/I of 1.6 (95% CI, 1.18 to 2.25). The T/Is for all individual marked groups were greater than one; however, the lower limit of the 95% CI for three of the five groups was less than one (Achord et al. 1992). Similarly, for the 1988 study, the T/I was 1.6, with a 95% CI between 1.0 and 2.6.

Subyearling Chinook Salmon

McNary Dam Studies

Barge transportation of subyearling chinook salmon was first evaluated at McNary Dam in 1983 and a subsequent 3-year study was conducted from 1986 through 1988. For the 1983 study, significantly more transported than inriver-migrating study fish were recovered as adults, with a T/I of 2.9. For the three later studies, T/Is were 2.8 (95% CI of 1.4 to 5.6) for 1986, 3.5 (95% CI of 1.7 to 7.1) for 1987, and 3.3 (95% CI of 1.3 to 9.4) for 1988 (Harmon et al. 1996).

Steelhead

Snake River Studies

Barge transportation of juvenile steelhead was evaluated annually at Lower Granite Dam during the 4-year period from 1977 through 1980 and was evaluated again at the dam in 1986 and 1989. For the four earlier studies, significantly more transported than inriver-migrating study fish returned from each test, with T/Is ranging from 1.7 to 17.5. Results from the studies conducted in 1986 and 1989 were the same as from the earlier studies. The T/Is were 2.0 (95% CI between 1.4 and 2.7) and 2.1 (95% CI between 1.3 and 3.5) for 1986 and 1989, respectively (Matthews et al. 1992, Harmon et al. 1995).

Due to recent listings of Snake River steelhead, a new series of studies to evaluate the benefits of transporting steelhead from Lower Granite Dam was initiated in 1999. The experimental design of these new studies follows the same protocols that began in 1995 for yearling chinook salmon. Final adult returns from the new steelhead studies will not be available for several years.

McNary Dam Studies

In 1979 and 1980, steelhead were marked at McNary Dam for barge transport evaluations. In both tests, significantly more transported than inriver-migrating control fish were recovered as adults. T/Is were 3.0 and 1.4 for the two respective years (Park et al. 1984, Park 1985).

TRUCK VS. BARGE TRANSPORT EVALUATIONS

Barges were first evaluated and used in the Snake River transportation program in 1977, after most truck transport studies were completed. Prior to that time, all transportation studies were conducted by truck. Therefore, opportunities to directly compare truck vs. barge transportation were limited. Park (1985) reported the information in Table 1 for trucked vs. barged studies.

Table 1. T/Is for truck vs. barge transport studies for chinook salmon and steelhead.

Year	Location	Species	Truck	Barge	Significant?
1978	Lower Granite Dam	yearling chinook salmon	5.8	8.9	yes
1978	Lower Granite Dam	steelhead	4.4	5.2	no
1979	McNary Dam	steelhead	2.1	3.0	no
1980	McNary Dam	steelhead	1.3	1.4	no
1983	McNary Dam	subyearling chinook salmon	3.2	2.9	no

On the Snake River, a single study comparing the two techniques was conducted with yearling chinook salmon at Lower Granite Dam in 1978. Park (1985) reported high overall T/Is for both test groups--5.8 for trucked fish and 8.9 for barged fish (99 adult returns for both transport test conditions combined); however, results differed significantly between the two treatment groups. In his report, Park appropriately concluded “This comparative test should be repeated because it was done for only 1 year, and similar comparisons with steelhead and fall chinook salmon have shown no significant benefit for barging” [over trucking]. Unfortunately, the study was never repeated (Matthews 1999). For three studies on steelhead and one on subyearling chinook salmon, there were no significant differences in adult return rates between the two treatments, although barged fish tended to return at somewhat higher rates than trucked fish. This may have resulted from differences in the release locations for the two groups. The barged fish were released 4-5 km downstream from Bonneville Dam while the trucked fish were released into the tailrace of the dam. Under present transportation procedures, nearly all fish trucked in summer are now taken by a ferry for release into mid-river downstream from Bonneville Dam. In all of the above studies, fish from both transport procedures returned at significantly higher rates compared to inriver migrants (Matthews 1999).

TRUCK TRANSPORT--CONTEMPORARY ISSUES AND APPLICATION

In a February 27, 1998 response to questions posed by the Implementation Team, the Independent Scientific Advisory Board (ISAB 1998) concluded that "Trucks should not be used in the transportation program due to a lack of information needed to advise management, due to the absence of current research programs to collect such information, and because historical indications on truck transport are negative."

The ISAB's statement that "historical indications on truck transport are negative" was based on evidence from two studies not involving transport from Corps of Engineer (COE) dams. Trucks were used in all transport studies conducted from COE dams between 1968 and 1976. Of 11 studies conducted on yearling chinook salmon, SARs of transported fish compared to inriver migrants were higher in 9 of the tests and significantly higher in 5 of the tests. For steelhead, significantly more adults returned from the truck-transported than the inriver-migrant groups in all 12 tests conducted during the period. The extent to which the results were biased by releasing trucked fish along the shoreline is unknown. Furthermore, there is no information to suggest a straying/homing problem from trucking occurred during the Snake River studies, although, admittedly, there are not a lot of data.

At present, in the lower Snake River, juvenile fish are transported by truck for approximately 2 weeks early in the season (late March to the second week in April), and from mid-to-late-June to the end of the transport season at the end of October. Transport by barge occurs in the interim. Likewise at McNary Dam, transportation (initially by trucking) begins when Hanford Reach subyearling chinook salmon predominate the daily collection and when inriver migratory conditions are deteriorating. Collection for transportation in recent years has occurred in June. Late season trucking from McNary Dam begins about the third week of July and continues until sometime in December, when concerns related to adverse weather/driving conditions preclude collection and transportation. Fish transported by truck in the early season, however, are released from the shoreline in daylight, rather than from mid-river, as occurs in the late trucking season. Therefore, potential for predation is a valid concern. There are several release points on both the Oregon and Washington sides of the Columbia River and fish truck personnel are familiar with river conditions at various flow levels and use discretion in choosing release sites affording reduced potential for predation.

From 1995 through 1998, 3.0, 1.9, 2.0, and 2.0%, respectively, of the yearling chinook salmon transported in the Snake River were transported by truck. Similarly, 3.1, 3.9%, 6.8, and 2.5% of the wild steelhead transported were transported by truck. In contrast, 97.4, 94.0, 91.8, and 90.7% of the subyearling chinook salmon transported were transported by truck. This is because most subyearling chinook migrate during summer after barging has been terminated in the Snake River.

In the lower Columbia River, 4.8, 71.3, 98.5 and 22.4%, respectively, of the yearling chinook salmon transported from McNary Dam from 1995 through 1998 were transported by truck. Similarly, 2.5, 81.6, 91.8, and 42.7% of the wild steelhead transported were transported by truck. In contrast, 6.3, 39.4, 64.9, and 4.1% of the subyearling chinook salmon transported were transported by truck. Although the percentage of yearling migrants transported by truck from McNary Dam is sometimes high, one must consider that there has been no transportation of yearling migrants from McNary Dam, except for very small numbers that are collected coincident with subyearling chinook salmon. All yearling migrants passing through the juvenile bypass system were returned to the river after PIT-tag detection.

REVIEW OF RECENT PIT-TAG DATA

Reviews of earlier NMFS transportation research generally concluded that fish released as controls in the earlier studies were not “true” controls because they were transported to release sites (Mundy et al. 1994, Ward et al. 1997).

To address this issue, the NMFS began new studies to evaluate transportation of yearling chinook salmon from Lower Granite Dam in 1995. All fish in the new studies were individually marked with PIT tags. Daily, a group of fish was loaded into barges for transportation. Another group was released directly back to the tailrace of Lower Granite Dam via a new bypass outfall pipe designed and located to release fish into favorable migratory conditions. The development by NMFS of PIT-tag detection and diversion (slide gates) systems at collection facilities downstream from Lower Granite Dam ensured that inriver migrants were not transported. Any fish that was released inriver and inadvertently transported from a downstream dam was identified and removed from the study. As reported above, results indicated that approximately twice as many transported as inriver study fish returned as adults.

In late 1997, NMFS and Idaho Fish and Game biologists began a detailed examination of wild and hatchery steelhead and spring/summer chinook salmon adult returns from fish that were PIT-tagged in 1993 (PIT-tagged as parr, but migrated in 1994), 1994, or 1995 and released at sites upstream from Lower Granite Dam. PIT-tagged fish that migrated in 1994 and 1995 and were collected in the bypass systems at Lower Granite, Little Goose, Lower Monumental, and/or McNary Dams and were detected by PIT-tag electronic detection systems were sorted into different categories depending on their detection histories at the four dams. At each dam, fish were either detected and transported, detected and bypassed back to the river, or were not detected (presumably passed the dams via spill or turbines). A small number of fish were detected but their fate was unknown. The two categories given the most attention recently are: (1) fish transported at Lower Granite and Little Goose Dams and (2) fish that passed through the four dams undetected. The number of transported fish was known, but the number of fish that passed through the system but were not detected was estimated.

Inriver migration conditions varied between the two years. In 1994, flows were considered somewhat below average and system spill levels were low. In 1995, flows were slightly better than average and moderate spill levels were provided at all dams downstream from Lower Granite Dam throughout the migration period. Adult returns from the 1994 and 1995 juvenile migrations are complete.

Statistical analyses that compared SARs among different detection history categories, with associated variance estimates indicated transportation showed varying potential benefits. However, variance estimation is complicated because variability is introduced at several steps in the process of estimating adult return rates, and the variance components interact in mathematically complex ways. Statistical inference for comparisons involving data from the studies of PIT-tagged fish released above Lower Granite Dam are only possible when appropriate variance estimates are determined. In many cases, insufficient statistical power exists to detect true differences between groups because of relatively small adult return numbers and/or imprecise return rate estimates. Adult return numbers from the 1995 juvenile migration were high enough to find significant differences between adult return rates for some migration-history categories. For PIT-tagged yearling chinook salmon released from Lower Granite Dam in 1995, estimated T/Is for the group never detected again after being marked and released at the dam ranged from 0.63 to 1.67 with fairly narrow 95% confidence intervals relative to the intervals for other data sets of fish released above Lower Granite (NMFS unpublished data). Additionally, based on analyses of PIT-tag data for fish tagged above Lower Granite Dam from 1994 through 1998 (Tables 3 and 4), the following patterns were observed:

1. Fish detected at multiple dams returned at a lower rate than fish transported or detected at only one dam.

Table 2. Smolt-to-adult return percentages (SAR) and numbers of adults returning to Lower Granite Dam for hatchery and wild yearling chinook salmon smolts PIT tagged and released above the dam from 1994 through 1998. Adult returns are complete only through 14 September 1999. Results are given for fish transported from Lower Granite or Little Goose Dams (Trans), bypassed at one (Once) or more (> Once) dams, or not detected (i.e. assumed to pass through spillways or turbines at all dams) at any dam (ND).

Year	Passage category	Hatchery		Wild	
		SAR	Adults	SAR	Adults

Year	Passage category	Hatchery		Wild	
1994	Trans	0.09	3	0.65	13
	Once	0.06	3	0.17	3
	> Once	0.00	0	0.13	1
	ND	0.11	7	0.18	6
1995	Trans	0.76	26	0.36	9
	Once	0.34	48	0.35	19
	> Once	0.25	49	0.19	20
	ND	0.40	27	0.43	9
1996	Trans	0.21	6	0.48	2
	Once	0.12	30	0.17	5
	> Once	0.11	20	0.17	5
	ND	0.17	29	0.22	4
1997	Trans	0.83	219	1.59	4
	Once	0.56	180	0.71	8
	> Once	0.48	76	0.90	9
	ND	0.61	147	1.56	14
1998	Trans	0.23	130	0.07	1
	Once	0.12	46	0.07	4
	> Once	0.08	29	0.10	8
	ND	0.21	48	0.18	4

Table 3. Smolt-to-adult return percentages (SAR) and numbers of adults returning to Lower Granite Dam for hatchery and wild steelhead smolts PIT tagged and released above the dam from 1994 through 1998. Adult returns are complete only through 14 September 1999. Results are given for fish transported from Lower Granite or Little Goose Dams (Trans), bypassed at one (Once) or more (> Once) dams, or not detected (i.e. assumed to pass through spillways or turbines at all dams) at any dam (ND).

Year	**Passage category**	**Hatchery**		**Wild**	
		SAR	**Adults**	**SAR**	**Adults**
1994	Trans	0.57	22	1.02	9
	Once	0.04	4	0.28	2
	> Once	0.01	1	0.16	1
	ND	0.14	7	0.83	6
1995	Trans	0.73	22	0.00	0
	Once	0.47	31	0.23	3
	> Once	0.24	37	0.14	4
	ND	1.49	11	0.00	0
1996	Trans	0.39	7	1.16	2
	Once	0.32	31	0.46	6
	> Once	0.16	17	0.26	4
	ND	0.39	14	0.35	2
1997	Trans	0.41	8	0.32	1
	Once	0.11	11	0.15	2
	> Once	0.10	12	0.09	2
	ND	0.14	6	0.00	0
1998	Trans	0.00	0	0.24	1
	Once	0.03	2	0.11	2
	> Once	0.05	5	0.08	21
	ND	0.21	7	0.26	21

2. In most cases, fish transported from McNary Dam in 1994 returned at a lower rate than fish transported from other dams.

3. From the 1994 juvenile migration, wild and hatchery steelhead and wild spring/summer chinook salmon transported from Lower Granite and Little Goose Dams combined returned at higher rates than those that passed through the hydropower system undetected under existing conditions. However, the reverse occurred for hatchery spring/summer chinook salmon in 1994 and hatchery steelhead in 1995 (no adult returns for wild steelhead for either group from 1995).

4. From the 1995 juvenile outmigration, wild spring/summer chinook salmon transported from Lower Granite and Little Goose Dams combined returned at a lower rate than those that passed through the hydropower system undetected under existing conditions.

5. In both 1994 and 1995, approximately 5 to 15% of the estimated population of PIT-tagged fish that arrived at Lower Granite Dam migrated undetected to below McNary Dam.

6. From the 1996 juvenile migration, preliminary analyses of adult returns indicated that hatchery and wild spring/summer chinook salmon and wild steelhead tagged and released above Lower Granite Dam then transported from Lower Granite and Little Goose Dams combined returned at higher rates than those that passed through the hydropower system undetected (NMFS unpublished data). For hatchery steelhead, SARs of the two groups were equal.

7. From the 1997 juvenile migration, preliminary analyses of incomplete returns indicate that, to date, hatchery and wild spring/summer chinook salmon and steelhead tagged and released above Lower Granite Dam then transported from Lower Granite and Little Goose Dams combined returned at higher rates than those that passed through the hydropower system undetected.

Most of the above observations are based on SARs of groups of fish that were comprised of few adults. Thus, in most cases, although point estimates of SARs for transported or non-detected fish were different (higher vs. lower or vice versa) depending on species and origin, no significant differences in SARs were observed. The potential for a “delayed” transport mortality will require further investigation.

BEHAVIOR

Impaired swimming performance might reduce juvenile survival following their release. Chinook salmon swimming performance has been evaluated before and after barging and no clear trends have been observed (Schreck and Congleton 1994).

Fish behavior has been examined (using underwater video) in raceways and in barges during transport. Most of the observed interactions were startle responses of undetermined cause. Classic aggressive behaviors were rarely observed. The behavior of yearling chinook salmon immediately after their release was also monitored using radiotelemetry. The information provides an estimate of the downstream migration speed for each radio-tagged fish, gives the minimum number of tagged fish successfully migrating through the prescribed release area, and allows estimates of their migration time and rate of survival from smolt release below Bonneville Dam to their arrival at the estuary. At release, most of the radio-tagged fish from barges moved downstream at a rate of 1 to 2 miles per hour. The majority of the tagged fish reached the estuary in 36 to 72 hours after release (Schreck and Congleton 1994). Radio-tagging studies indicate that run-of-river yearling hatchery chinook salmon migrate faster than do barged hatchery chinook salmon released at the same time and under the same flow conditions. Run-of-river fish also appear to travel in tighter groups than do barged fish. The authors speculate that the observed difference in travel time may result from some difference in fish condition. However, the barged chinook salmon groups were known Snake River stocks, whereas the run-of-river chinook salmon collected and tagged at Bonneville were not. The authors also speculated that an insufficient degree of smoltification, or osmoregulatory or other disturbances associated with transportation, may potentially delay ocean entry (Schreck and Davis 1997).

STRAYING/HOMING IMPAIRMENT

According to Quinn (1993), “straying is the migration of mature individuals to spawn in a stream other than the one where they originated. From the standpoint of orientation, a salmon strays if it ascends a non-natal river and does not subsequently make its way to its natal river. If a fish enters a hatchery, it is seldom given the chance to retreat, so there is some question as to whether ‘strays’ entering hatcheries would have eventually left.” Further, “estimates of straying vary greatly between hatcheries and rivers, so general statements on straying proportions have minimal biological significance.”

Natural Straying Rates

A study by Shapovalov and Taft at Scott and Waddell Creeks (California) found that steelhead strayed between the creeks at rates of 2 and 3% percent, respectively. Another study by McIsaac on the homing of wild, wild/hatchery (reared 10 weeks in a hatchery), and hatchery fall chinook in the Lewis River (Washington) found that the wild chinook strayed at a rate of 3.2%. Wild salmon have also been observed to stray into hatcheries. Nicholas and Van Dyke estimated that 64.7% of the wild coho salmon returning to the Yaquina River watershed (Oregon) in 1981 entered the Oregon Aqua-Foods hatchery (reported by Quinn 1993).

Straying Rates of Transported Snake River Fish

There is no direct evidence to show that wild and hatchery salmon, transported from Snake River dams as juveniles, wander into non-natal rivers at higher rates than would occur naturally. Reported rates of straying among transported fish are in the range of natural straying rates (1 to 3%). Marked steelhead from transport study groups (control and transported) have been reported in the Deschutes River (Oregon). Specifically, during the truck-transport studies conducted during 1970 through 1973 at Little Goose Dam, the T/Is were the same for adult steelhead recovered from the Deschutes River as for those captured at Little Goose Dam. This indicated that the trucked fish were not straying into the Deschutes River at a higher rate than did fish that migrated inriver as smolts. Further, in studies conducted between 1975 and 1980, 11 spring/summer chinook salmon (0.9% of the run), and 16 steelhead adults (0.2% of the run) were identified as "strays." All were transported from Lower Granite or Little Goose Dams. Among the steelhead, 11 of the 16 were released in 1976 (before barge transport began). All of the chinook salmon were observed in the Deschutes River (Oregon), whereas, the steelhead were observed at Wells Hatchery (9), the Deschutes River (3), Big Creek Hatchery (1), Chelan Hatchery (1), and the Yakima Hatchery (1). Ebel (1980) concluded, and Park (1985) agreed, that straying had a minimal impact on the overall adult returns to expected spawning areas.

In analyzing steelhead returns, Park (1985) reported that about 10% of the transported fish exhibited a consistent but small delay during their upstream migration. The proportions of transport to control adults returning over Lower Granite Dam were higher during spring than during fall, implying a delay for the transported fish. Further analysis indicated that transporting B-run steelhead originating in the Clearwater River caused a minor delay in their upstream passage (Park 1985). Matthews (1992) later postulated that the delay Park noted was more likely due to a slightly later river entry timing for adults returning from groups that were transported as juveniles. This was not observed in the A-run steelhead because most were above the dams when their migrations ceased the previous fall; therefore, they would not have been observed at the dams during the spring migration. Because B-run steelhead migrate later than the A-run, the late segment of that population would over-winter in the reservoirs below the dams and could thus be observed the following spring when they continued their migration. This may have been occurring in the A-run as well, but it simply was not observed. In any event, the slight difference in run timing, if it was real, did not appear to affect the ability of steelhead to return to the hatcheries in time to spawn successfully.

Straying During Priest Rapids Dam Transport Studies

Transportation of spring chinook and sockeye salmon juveniles from Wanapum and Priest Rapids Dams was researched from 1984 through 1988. These studies indicated that jaw-tagged sockeye adults (that were transported as smolts) took longer to reach Priest Rapids Dam than did the control groups in two of five years; chinook salmon adults took longer in one of three years. Jaw-tagged sockeye and chinook salmon adults from transported groups fell back below Bonneville Dam more often than did control group adults, and sockeye salmon transported solely by truck fell back more often than did sockeye salmon transported partially by barge. These results suggested that transportation impaired homing (expressed as migration delay) somewhat in adult sockeye salmon between Bonneville and Priest Rapids Dams. The studies did not, however, indicate that sockeye or chinook salmon homing was impaired between Priest Rapids Dam and spawning areas above the dam. Coded-wire tag (CWT) recoveries from sockeye salmon suggested straying occurred in four truck-transported and four control fish from the 1985 tests. Other CWT recoveries included two truck-transported and one trucked/barged sockeye salmon from the 1987 tests. The authors did not view those 11 strays as excessive—though straying likely exceeded the number estimated from other CWT records. For example, two jaw-tagged and truck-transported sockeye adults from the 1985 study were found in the Lewis River. For chinook salmon that were transported by truck, four strayed in 1984 and eight strayed in 1985. However, all of these fish had passed hatchery weirs and, therefore, could not return downstream. According to the authors, the fact that all but 1 of the 12 were from transported groups may indicate more wandering by chinook salmon trucked as juveniles. The authors cautioned that homing results observed in transported and control sockeye and chinook salmon have relevance primarily for the conditions that were created for their study on the mid-Columbia River and may or may not have relevance elsewhere for trucked or trucked/barged sockeye salmon or to other species barged from COE dams (Chapman et al. 1997).

More recently, concerns have been raised over a reported increase in out-of-basin hatchery steelhead reported in the Deschutes River (Oregon). Deschutes River hatchery steelhead receive distinctive marks so non-native steelhead are identifiable at hatcheries and weirs. It has been suggested, based on the timing of these observations, that the majority of these fish remained to spawn in the Deschutes River. Since spawning between native and out-of-basin stocks can impact genetic viability, there is valid cause for alarm. However, observations of non-Deschutes hatchery steelhead at Sherar Falls and at upstream hatcheries have increased concurrent with decreasing proportions of steelhead transported from the Snake River. There is no direct evidence to show that the increased straying of steelhead into the Deschutes River is related to the juvenile fish transportation program.

Research that was conducted from 1992 to 1994 comparing the survival of steelhead transported to Tongue Point with that of steelhead transported to the traditional release site below Bonneville Dam provides some information regarding the straying of transported fish into the Deschutes River. Overall adult returns through 1996 (preliminary results), showed that 573 steelhead returned to Lower Granite Dam and 9 were observed in the Deschutes River. This is therefore, a straying rate of 1.6%, well within expected natural straying rates. There were no marked inriver groups for comparisons in the aforementioned studies. Information from the 1986 and 1989 transportation evaluations at Lower Granite Dam showed that 1 of 500 returning adult steelhead (0.2%) was observed in the Deschutes River. Pooling all the available information from the 1986, 1989, and 1992 through 1994 studies showed that 10 of 1,073 (0.9%) transported adult steelhead strayed into the Deschutes River (Marsh et al. 1997 and unpublished NMFS data).

DIRECT TRANSPORTATION MORTALITY

There are a number of reasons fish die during the collection, holding/loading, transport, and release process. Some losses can be directly observed in various parts of the juvenile collection system (i.e., gatewells, wet separators, raceway screens, barge compartments, etc.). Other sources of mortality cannot be observed directly (e.g., impingement on screens and potential predation in raceways and during transport). Mortality following release, which may be related to the transportation experience, is not observable but may occur, for example, through increased susceptibility to predation or disease. Overall collection facility mortality has been observed to range from 0.1 to 8.9%, depending on the individual collection facility, the species, and life stage (COE 1997).

There are no precise data on juvenile mortality during the actual transportation process. Data from radio-tagged chinook released below Bonneville provide some information on immediate survival following release from barges. The COE estimates that average seasonal direct mortality (observable mortality before and during transport and at release) for collection and transportation combined is less than 2% (COE 1993). The PATH group also assumes a 98% transportation survival (Marmorek and Peters 1998). Stress, injury, and disease transmission are potential causes of transport-related mortality. Larger salmonids may prey upon injured, moribund, or smaller salmonids during transportation. However, observations (using video cameras) have rarely shown aggressive behavior or dead fish on the bottom of barge compartments during release. Collection facilities and operational procedures that may contribute to mortality continue to be researched.

Studies conducted from 1992 through 1996 showed no evidence of large-scale predation on smolts immediately following their release from the barges (Schreck et al. 1993a,b; 1994; 1995a,b; 1996; 1997). Using fixed and mobile radio-tracking methods, the above studies evaluated the behavior, migration speed, and migration routes taken by radio-tagged Snake River yearling chinook salmon during and after their release from transportation barges. The studies also afforded a minimum survival estimate to the lower Columbia River estuary. More recent efforts have compared the behavior of barged yearling chinook salmon with that of run-of-river yearling chinook salmon collected at Bonneville Dam. In 1996, 79 to 92% of the radio-tagged, barged yearling chinook salmon and 77 to 97% of the run-of-river yearling chinook salmon successfully reached the lower Columbia River estuary. In the 1997 studies, 74 to 97% of both groups of the radio-tagged yearling chinook salmon survived to near the estuary (Schreck and

Davis 1997). The release date made no difference in the proportion of barged yearling chinook salmon reaching the estuary (P = 0.60, chi-square test), nor was there any statistically significant difference between the barged and run-of-river groups (P = 0.34, chi-square test, pooled release dates). In the 1996 tests, fish condition (as reflected by level of descaling) did not appear to affect the survival of radio-tagged yearling chinook salmon. There was no difference between individuals with greater or less than 10% descaling in either the proportion of fish reaching the estuary or in the rate of mortality within the estuary (Schreck and Davis 1997).

Data on the survival of yearling chinook salmon classified as "descaled" during marking at Lower Granite Dam are available in the NMFS 1995 transport vs. inriver migration survival study. The reported 24-hour delayed mortality of study fish was 1.6%. At the time of tagging, 4% of the juvenile chinook salmon were recorded as descaled. Twenty percent of the observed 1.6% 24-h delayed mortality were listed as descaled at tagging. Of 866 returning adults, 5% were listed as descaled at tagging. These data suggested that descaling may affect short-term survival, but may not be a factor in overall survival to adult return (NMFS unpublished data).

Mortality of intentionally descaled chinook salmon and steelhead held at the Lower Granite Dam juvenile facility did not differ significantly from mortality observed in the control groups. Of the fish that died, in both the descaled and the control groups, 75% of the chinook and 44% of the steelhead developed fungal infections prior to death. These fungal infections normally appeared on the fins rather than on the descaled areas or elsewhere on the body (Congleton et al. 1997a).

STRESS AND TRANSPORTATION

In the early 1980s, researchers began evaluating facilities used for the collection, bypass, and transport of outmigrating juvenile anadromous salmonids. The response of juvenile salmon has been assessed by measuring various physiological, performance, and behavioral traits. Studies show that collection facilities and procedures increase stress among juvenile salmonids. Much of what has been learned from this work has been directly applied to management of the juvenile fish transportation program (i.e., addition of pre-anesthesia systems, open-channel flumes, shaded raceways, enlarged barge release exits, etc.). However, nearly all of the information concerning the impacts of the transportation process on the physiology and performance of migrating smolts has been derived from experiments with hatchery fish (Schreck and Davis 1997).

Recovery From Stress

Elevated plasma cortisol levels associated with stress induced by handling and marking procedures have been found to decrease significantly (to pre-mark levels) during 3 hours of truck transportation (Matthews et al. 1987). The results of a 1993 study indicated that, even though stress indicators in juvenile salmonids were initially elevated (plasma cortisol, white blood cell levels, composition of white blood cells, diminished avoidance behavior), they decreased as the fish were barged downriver (Schreck and Congleton 1993). Studies in 1994, however, showed that the ability of yearling chinook salmon sampled from a barge at Lower Granite Dam to survive a saltwater challenge was reduced on each of three successive test dates over the course of the juvenile migration (Schreck and Congleton 1994). More recent studies (early season trials) indicated that elevated blood plasma cortisol levels (a physiological indicator of stress) in barged chinook salmon and steelhead largely returned to normal during the trip downriver. However, at the peak of the migration, plasma cortisol levels in yearling chinook salmon remained elevated throughout the collection and transportation process (Schreck et al. 1995a). Results from late season trials have been mixed.

Stress Response Differences between Hatchery and Wild Fish

Plasma cortisol concentrations taken from yearling chinook salmon in barges at Lower Granite Dam were consistently and significantly higher in wild than hatchery fish throughout the migration. The highest cortisol concentrations in both groups occurred during peak movement of juvenile chinook salmon into the collection facility (Schreck and Congleton 1994). These data suggested that recovery from collection and loading stressors is related to loading density. Mixing species together during collection and transportation may also have been a factor.

Steelhead Stress Response

Studies in 1994 and 1995 demonstrated that collection and loading were also stressful to steelhead smolts. Recovery from stress appeared to vary widely over the course of the migration season, ranging from below, at, or above pre-collection levels. It is of interest to note that in the 1994 studies, stress indices did not decline to pre-collection levels during barge transportation to below Bonneville Dam or even to Tongue Point (an additional 20 hours of potential recovery time) (Schreck et al. 1995a).

In 1997, a laboratory experiment was conducted to determine how well steelhead tolerated a stressful event: the water level was lowered for 15 minutes at various intervals after intentionally descaling 20% of the upper body surface. The fish were sampled 16 hours after the stress event. Both descaling and exposure to low water level resulted in significant increases in enzyme levels. However, no statistically significant interactions between descaling treatment and stress exposure were found, thus suggesting that the responses to the stressor were similar for descaled and control fish at all times after descaling (Congleton et al. 1997a).

Mixed Species Stress Effects on Juvenile Chinook Salmon

Laboratory studies intended to simulate transportation practices were conducted in 1995 and 1996. Results indicated that the presence of rainbow trout (surrogate steelhead) affected the behavior and physiology of juvenile hatchery chinook salmon (Willamette River stock). Behavioral data indicated that the rainbow trout were very aggressive, while the chinook salmon were passive. In confinement, the schooling behavior of the chinook did not appear to be compatible with the territorial behavior of the rainbow trout. Physiological studies found that plasma cortisol levels were higher in chinook salmon after rainbow trout were introduced than were plasma cortisol levels in chinook salmon in control tanks (no loading) or in tanks loaded with additional chinook salmon. A second experiment found that plasma cortisol levels in chinook salmon that received inflow containing rainbow trout odor were initially similar to control group levels. However, plasma cortisol levels increased 2 hours after the odor was introduced (Kelsey 1997; Schreck et al. 1995b). These data support the need for improving fish size-separation to reduce species interactions.

DISEASE AND TRANSPORTATION

The incidence of bacterial kidney disease (*Renibacterium salmoninarum*) (BKD) and the potential for its transmission between wild and hatchery stocks of yearling chinook salmon collected for transport has been investigated by the U.S. Geological Survey, Biological Resource Division (formerly the National Biological Survey). The purpose of this research was to determine if BKD contributed to poor survival of yearling chinook salmon smolts (Elliott and Pascho 1993; 1994a,b). Laboratory cohabitation and waterborne experiments indicated that the causative agent of BKD can be transmitted to healthy chinook salmon smolts during a 48-hour exposure to infected chinook salmon. Results of the 1992 studies indicated a high concentration level of *R. salmoninarum* (1×10^5 cells per ml) may be required to infect more than 50% of the exposed fish within a 48-hour period (Elliott and Pascho 1994a).

Blood plasma samples taken from yearling chinook salmon in gatewells and barges at Lower Granite Dam, and from fish in the barges after transport, indicated that defenses against disease pathogens are significantly decreased after transportation (Schreck and Congleton 1994). In 1996, several assays were examined to determine their usefulness in evaluating the effects of stress on immune system function. Spring chinook salmon juveniles (mid-Columbia River origin stocks) were held under crowded and uncrowded conditions (0.5 lb fish/gal vs. 0.05 lb fish/gal density) and sampled at 3-, 7-, 14-, and 21-day intervals. Interferon (a factor involved in resisting viral diseases) was moderately lower than measured in the controls in one trial and was unaffected in a second trial. Oxidative burst activity by blood neutrophils (a factor involved in eliminating pathogens) was significantly depressed in the groups of crowded fish at all time periods.

From 1988 through 1992, researchers evaluated the prevalence (frequency of occurrence) and severity (degree of infection) of *R. salmoninarum* among fish in marked groups of Columbia and Snake River hatchery yearling chinook salmon, both before their release and during their seaward migration. During the study, the prevalence of infection decreased in six of the eight hatchery groups. The researchers attributed this decrease to changes in hatchery practices that reduced vertical and horizontal transmission of the infection (Maule et al. 1996).

The 1988 through 1992 studies also found that yearling chinook salmon from Snake River hatcheries had a higher prevalence of *R. salmoninarum* infections when they were sampled at dams than in the hatcheries; no similar differences were noted in comparisons of Columbia River fish. The authors thought these differences between Snake and Columbia River fish might have resulted from differing inriver conditions and the distances from the hatcheries to the dams. They assumed that after being released from a hatchery, the most severely infected fish would die first. Therefore, increases in the prevalence and severity of infection suggest that the infection progressed during the migration. The fact that increased prevalence and severity was detected in the Snake River but not in the Columbia River, suggested that the changes were caused by the river environment and not by the decreased disease resistance of fish during smoltification. The authors concluded that differences in water temperature and longer migration times caused hatchery fish migrating in the Snake River to experience higher prevalence and severity of *R. salmoninarum* than did those in the Columbia River (Maule et al. 1996).

Live-box studies suggested that, under certain conditions, uninfected salmonid smolts could become infected with *R. salmoninarum* (presumably shed from infected smolts) during inriver migration or transportation. These studies, however, did not define the levels of waterborne *R. salmoninarum* necessary for the normal smolts to become infected, nor did they define the probability of transmitting the disease from smolts with known infection levels to uninfected smolts (Elliott and Pascho 1995). Studies have shown that, in most years, the highest mean antigen levels were measured in fish sampled after 75% of the total migration had passed a given dam. It is of particular significance to note that when the largest numbers of fish were being collected for bypass or transportation, mean antigen levels were relatively low (Elliott et al. 1997).

The juvenile fish transportation program has established criteria that govern holding and loading operations. Specifically, collected fish may not be held longer than 2 days, and there is a maximum loading density of 0.5 lb fish/gal water. This density is normally only attained during peak spring migration periods when fish are transported by barge. Juvenile fish transport by barge from Lower Granite Dam normally takes about 35 to 40 hours, depending on weather conditions. According to Maule et al. (1996), decreasing the loading densities in raceways and ponds enhances specific immune responses of juvenile salmon. Therefore, the combination of segregating juveniles and reducing the holding and loading densities may decrease the potential to transmit of *R. salmoninarum* and enhance the ability of fish to resist the pathogen. Finally, even if BKD is transmitted from fish-to-fish, nearly all smolts arriving at the dams will have been previously infected.

Research has clearly demonstrated the high prevalence of BKD in anadromous salmonid smolts originating in the Columbia and Snake Rivers. However, whether or not transportation exacerbates mortality due to the disease is unknown.

KEY UNCERTAINTIES

In 1994, the Independent Peer Review Team (IPRT) completed a review of the data available on the benefits of transporting juvenile fish (Mundy et al. 1994). The IPRT findings and conclusions indicated that "the kinds of Snake River salmon for which transportation is likely to improve relative survival to the point of transportation are the steelhead, and to a lesser degree, the yearling-migrant stream-type chinook salmon designated as "spring/summer chinook" salmon by NMFS."

Although transportation research has been ongoing for a long period, uncertainties remain. Only recently has technology advanced to the point where accurate and precise information can be gathered.

There is concern that control groups of fish from the past transportation studies may not have represented the run-at-large, since these fish were collected and marked after passing through a juvenile bypass system. The effects and potential bias of this so called "handling" is the subject of continued debate.

To address some concerns with past study designs, transportation study fish will have to be marked prior to their arrival at dams, as was first proposed by NMFS in the early 1990s. At present, this is only occurring with hatchery fish. Ideally, sufficient numbers of wild fish could be marked in natal areas upstream from the dams so that their origins would be known, providing the possibility to evaluate adult homing to individual natal streams. These types of studies will not be possible on wild stocks until abundance increases considerably.

The recently initiated PIT-tag studies are beginning to demonstrate the tremendous within and between year and, most likely, decadal variability inherent in the adult return rates of anadromous salmonids. This variability reflects the tremendous life-history variation among different salmon stocks and the environments within which they exist. Sufficient long-term data sets that are based on PIT-tagged fish and that provide conclusive evidence about SARs of transported fish versus downstream migrants are not now available. To provide sufficient data will require marking of fish for several more years and complete adult returns will not become available for another decade. These studies should include truck evaluations when possible. The studies will need to evaluate wild stocks independently whenever possible, as results derived from hatchery fish may not represent wild stocks. The ISAB recommended that wild fish be evaluated by individual stream or stock. These evaluations are not now possible, given the low population abundances and low adult return rates in recent years. However, individual stock evaluations may be possible in the future as stocks rebound.

There is uncertainty regarding the levels of post-transport and post-bypass delayed mortality. Evaluations of post-transport and post-bypass delayed mortality should receive high priority.

Based upon previous data generated from studies conducted at COE dams, the most that can be said regarding homing of returning adults that were transported as juveniles is that transport does not appear to result in a large amount of homing impairment. Research to accurately and precisely characterize the effects of transportation as juveniles on the homing characteristics of returning adults should be conducted. Installation of adult PIT-tag detectors at mainstem dams will be critical for conducting this work.

REFERENCES

Achord, S., J. Harmon, D. Marsh, B. Sandford, K. McIntyre, K. Thomas, N. Paasch, and G. Matthews. 1992. Research related to transportation of juvenile salmonids on the Columbia and Snake Rivers, 1991. National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle, Washington. Report to U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington. Contract DACW68-84-H0034. 57 p. + appendices.

Carlson, C., and G. Matthews. 1991. Fish transportation studies -- Priest Rapids Dam, 1989. National Marine Fisheries Service, Coastal Zone and Estuarine Studies, Seattle, Washington. Report to Grant County Public Utility District, Ephrata, Washington. 80 p.

Carlson, C., and G. Matthews. 1992. Salmon transportation studies -- Priest Rapids Dam, 1990. National Marine Fisheries Service, Coastal Zone and Estuarine Studies, Seattle, Washington. Report to Grant County Public Utility District, Ephrata, Washington. 45 p.

Chapman, D., C. Carlson, D. Weitkamp, G. Matthews, J. Stevenson, and M. Miller. 1997. Homing in sockeye and chinook salmon transported around part of their smolt migration route in the Columbia River. North American Journal of Fisheries Management 17:101-113.

(COE) U.S. Army Corps of Engineers 1993. Endangered Species Act Section 10 permit application dated November 15, 1993; revised December 7, 1993.

(COE) U.S. Army Corps of Engineers 1997. Juvenile Fish Transportation Program, 1996. U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington. 109 p. + appendices.

Congleton, J., W. LaVoie, C. Schreck, L. Davis, and D. Elliott. 1997a. Evaluation of the effects of descaling on short-term survival of migrating juvenile salmonids. Abstract. In U.S. Army Corps of Engineers, 1997 Annual Research Review: Anadromous Fish Evaluation Program. U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington.

Congleton J., W. LaVoie, C. Schreck, L. Davis, and M. Fitzpatrick. 1997b. Evaluation of the effects of descaling on short-term survival of migrating juvenile salmonids, year 2. Idaho Cooperative Fish and Wildlife Research Unit, Boise, Idaho. U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington. 80 p.

Ebel, W. 1980. Transportation of chinook salmon, *Oncorhynchus tshawytscha*, and steelhead, *Salmo gairdneri*, smolts in the Columbia River and effects on adult returns. Fisheries Bulletin 78:491-505.

Ebel, W., D. Park, and R. Johnsen. 1973. Effects of transportation on survival and homing of Snake River chinook salmon and steelhead trout. Fisheries Bulletin 72:549-563.

Elliott, D., and R. Pascho. 1993. Juvenile fish transportation: impact of bacterial kidney disease on survival of spring/summer chinook salmon stocks. Abstract. U.S. Fish and Wildlife Service, National Fisheries Research Center, Seattle, Washington.

Elliott, D., and R. Pascho. 1994a. Juvenile fish transportation: impact of bacterial kidney disease on survival of spring/summer chinook salmon stocks. U.S. Department of the Interior, National Biological Survey, Seattle, Washington. Annual Report, 1992. 79 p. + appendices.

Elliott, D., and R. Pascho. 1994b. Juvenile fish transportation: impact of bacterial kidney disease on survival of spring/summer chinook salmon stocks. Abstract. In U.S. Army Corps of Engineers, 1994 Annual Research Review: Fish Passage Development and Evaluation Program. U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington.

Elliott, D., and R. Pascho. 1995. Juvenile fish transportation: impact of bacterial kidney disease on survival of spring/summer chinook salmon stocks. U.S. Department of the Interior, National Biological Service, Seattle, Washington. Report to U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington. Contract E86920048. 59 p. + appendices.

Elliott, D., R. Pascho, and L. Jackson. 1997. *Renibacterium salmoninarum* in spring-summer chinook salmon smolts at dams on the Columbia and Snake Rivers. Journal of Aquatic Animal Health 9:114-126.

Harmon, J., D. Kamikawa, B. Sandford, K. McIntyre, K. Thomas, N. Paasch, and G. Matthews. 1995. Research related to transportation of juvenile salmonids on the Columbia and Snake Rivers, 1993. National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle, Washington. Report to U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington. Contract No. DACW68-84-H0034. 43 p. plus Appendix

Harmon J., N. Paasch, K. McIntyre, K. Thomas, B. Sandford, and G. Matthews. 1996. Research related to transportation of juvenile salmonids on the Columbia and Snake

Rivers, 1994. National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle, Washington. Report to U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington. Contract DACW68-84-H0034. 18 p. plus Appendix.

Harmon, J., B. Sandford, K. Thomas, N. Paasch, K. McIntyre, and G. Matthews. 1993. Research related to transportation of juvenile salmonids on the Columbia and Snake Rivers, 1992. National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle, Washington. Report to U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington. Contract DACW68-84-H0034. 37 p. plus Appendix.

(ISAB) Independent Scientific Advisory Board. 1998. Response to questions of the Implementation Team regarding juvenile salmon transportation in the 1998 season. ISAB Report 98-2. National Marine Fisheries Service, Hydropower Program, Portland, Oregon.
21 p.

Kelsey, D. 1997. Effects of steelhead trout (*Oncorhynchus mykiss*) on chinook salmon (*O. tshawytscha*) behavior and physiology. M.S. Thesis. Oregon State University. 52 p.

Marmorek, D., and C. Peters (eds.). 1998. Plan for analyzing and testing hypotheses (PATH): preliminary decision analysis report on Snake River spring/summer chinook. Draft. ESSA Technologies, LTD., Vancouver, B.C., Canada. 92 p. + appendices

Marsh, D., J. Harmon, N. Paasch, K. Thomas, K. McIntyre, B. Sandford, and G. Matthews. 1997. Research related to transportation of juvenile salmonids on the Columbia and Snake Rivers, 1996. National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle, Washington. Report to U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington. Contract E86960099. 26 p. + appendices.

Matthews, G. 1992. Potential of short-haul barging as a bypass release strategy. Issue Paper. National Marine Fisheries Services, Northwest Fisheries Science Center, Seattle, Washington. 56 p.

Matthews, G. 1999. Truck transportation of juvenile salmonids at U.S. Army Corps of Engineers Dams. National Marine Fisheries Service, Northwest Fisheries Science Center, Fish Ecology Division, Seattle, Washington. 29 p.

Matthews, G., S. Achord, J. Harmon, O. Johnson, D. Marsh, B. Sanford, N. Paasch, K. McIntyre, and K. Thomas. 1992. Evaluation of transportation of juvenile salmonids and related research on the Columbia and Snake Rivers, 1990. National Marine Fisheries Services, Northwest Fisheries Science Center, Seattle, Washington. Report to U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington. Contract DACW68-84-H-0034. 52 p. + appendix.

Matthews, G., D. Park, J. Harmon, C. McCutcheon, and A. Novotny. 1987. Evaluation of transportation of juvenile salmonids and related research on the Columbia and Snake Rivers, 1986. National Marine Fisheries Services, Northwest Fisheries Science Center, Seattle, Washington. Report to U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington. Contract DACW68-84-H-0034. 35 p. + appendix.

Maule, A., D. Rondorf, J. Beeman, and P. Haner. 1996. Incidence of *Renibacterium salmoninarum* infections in juvenile hatchery spring chinook salmon in the Columbia and Snake Rivers. Journal of Aquatic Animal Health 8:37-46.

Mundy, P., D. Neeley, C. Steward, T. Quinn, B. Barton, R. Williams, D. Goodman, R. Whitney, M. Erho, and L. Botsford. 1994. Transportation of juvenile salmonids from hydroelectric projects in the Columbia River Basin; an independent peer review. U.S. Fish and Wildlife Service, Portland, Oregon. 149 p.

Park, D. 1985. A review of smolt transportation to bypass dams on the Snake and Columbia Rivers. National Marine Fisheries Service, Northwest Fisheries Center, Seattle, Washington. Report to U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington. Contract DACW68-84-H-0034. 66 p.

Park, D., G. Matthews, J. Smith, T. Ruehle, J. Harmon, and S. Achord. 1984. Evaluation of transportation of juvenile salmonids and related research on the Columbia and Snake Rivers, 1983. National Marine Fisheries Service, Seattle, Washington. Report to U.S. Army Corps of Engineers, Northwest Pacific Division, Portland, Oregon. Contract DACW68-78-C-0051. 39 p. + appendices.

Quinn, T. 1993. A review of homing and straying of wild and hatchery-produced salmon. Fisheries Resources 18:29-44.

Raymond, H. 1988. Effects of hydroelectric development and fisheries enhancement on spring and summer chinook salmon and steelhead in the Columbia River Basin. North American Journal of Fisheries Management 8:1-23.

Schreck, C., and J. Congleton. 1993. Evaluation of facilities for collection, bypass and transportation of outmigrating chinook salmon. Abstract. In U.S. Army Corps of Engineers, 1993 Annual Research Review: Fish Passage Development and Evaluation Program. U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington.

Schreck, C., and J. Congleton. 1994. Evaluation of facilities for collection, bypass and transportation of outmigrating salmonids. Abstract. In U.S. Army Corps of Engineers, 1994 Annual Research Review: Fish Passage Development and Evaluation Program. U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington.

Schreck, C., and L. Davis. 1997. Evaluation of migration and survival of juvenile salmonids following transportation. Abstract. In U.S. Army Corps of Engineers, 1997 Annual Research Review: Anadromous Fish Evaluation Program. U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington.

Schreck, C., L. Davis, and D. Kelsey. 1995a. Evaluation of facilities for collection, bypass, and transportation of outmigrating chinook salmon. Oregon Cooperative Fishery Research Unit, Department of Fisheries and Wildlife, Oregon State University, Corvallis, Oregon. Report to U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington. JTF-92-XX-3. 41 p.

Schreck, C., L. Davis, H. Lorz, and M. Beck. 1995b. Evaluation of procedures for collection, bypass, and downstream passage of outmigrating salmonids. Oregon Cooperative Fishery Research Unit, Department of Fisheries and Wildlife, Oregon State University, Corvallis, Oregon. Report to U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington. LGR-96-XX-1. 13 p.

Schreck, C., L. Davis, and C. Seals. 1996. Evaluation of procedures for collection, bypass, and transportation of outmigrating salmonids. Objective 1: Migratory behavior and survival of yearling spring chinook salmon in the lower Columbia River and estuary. Draft. Oregon Cooperative Fishery Research Unit, Department of Fisheries and Wildlife, Oregon State University, Corvallis, Oregon. MPE-96-10.

Schreck, C., L. Davis, D. Kelsey, and P. Wood. 1994. Evaluation of facilities for collection, bypass, and transportation of outmigrating chinook salmon. Oregon Cooperative Fishery Research Unit, Department of Fisheries and Wildlife, Oregon State University, Corvallis, Oregon. Report to U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington. 51 p.

Schreck, C., S. Kaattari, L. Davis, C. Pearson, P. Wood, and J. Congleton. 1993a. Evaluation of facilities for collection, bypass, and transportation of outmigrating chinook salmon.

Oregon Cooperative Fishery Research Unit, Department of Fisheries and Wildlife, Oregon State University and Idaho Cooperative Fish and Wildlife Research Unit, University of Idaho, Boise, Idaho. Report to U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington. 58 p.

Schreck, C., S. Kaattari, L. Davis, L. Burtis, P. Wood, J. Congleton, T. Mosey, S. Rocklage, and B. Sun. 1993b. Evaluation of facilities for collection, bypass, and transportation of outmigrating chinook salmon. Oregon Cooperative Fishery Research Unit, Department of Fisheries and Wildlife, Oregon State University and Idaho Cooperative Fish and Wildlife Research Unit, University of Idaho, Boise, Idaho. Report to U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington. 61 p.

Slatick, E., D. Park, and W. Ebel. 1975. Further studies regarding effects of transportation on survival and homing on Snake River chinook salmon and steelhead trout. Fisheries Bulletin 73:925-931.

Ward, D. L., R. R. Boyce, F. R. Young, and F. E. Olney. 1997. A review and assessment of transportation studies for juvenile chinook salmon in the Snake River. North American Journal of Fisheries Management 17:652-662.